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OBSERVATIONS OF THE EFFECT ON SPACECRAFT FUNCTION AND COMMUNICATIONS BY THE ESEX 26 kW AMMONIA ARCJET OPERATION

M.J. Dulligan*
ERC, Inc.
USAF Research Laboratory
Edwards AFB, CA

D.R. Bromaghim†, J.A. Zimmerman
USAF Research Laboratory
Edwards AFB, CA

D. Hardesty
Lockheed Martin Technical Operations
Dublin, CA

L.K. Johnson‡
Aerospace Corporation
El Segundo, CA

Abstract

Tests designed to detect the influence of operating the Electric Propulsion Space Experiment (ESEX) 26 kW ammonia arcjet on normal spacecraft communications and operations showed No? minimal, if any, adverse * affect. Two on-board antennas sensitive to the 2, 4, 8, and 12 GHz frequencies detected no increase in signal amplitude that is clearly identifiable with arcjet operation. Analysis of the bit-error rate (BER) tests, a sensitive diagnostic for quantitatively measuring the ~~a~~effect of the arcjet plume on ground/spacecraft round trip communication, revealed no obvious correlation between arcjet operation and the observed increases in bit-error rate. Finally, a series of qualitative observations consistently indicated the benign nature of arcjet operation on

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* Project Scientist

† ESEX Program Manager

‡ ESEX Chief Scientist, Present Address Jet Propulsion Laboratory, Pasadena, CA

normal spacecraft events. For example, commands uplinked without abnormal rejection rate and telemetry downlinked successfully during arcjet operation.

Introduction

On February 23, 1999, a Delta II rocket launched the USAF's Advanced Research and Global Observation Satellite (ARGOS) into an 850 km, 98.7° inclination orbit. The USAF Research Laboratory-sponsored Electric Propulsion Space Experiment (ESEX), one of nine manifested experiments, demonstrated operation of a 26 kW ammonia arcjet, becoming the highest powered system successfully operated on orbit prior to the International Space Station. The experimental objectives were to demonstrate the feasibility and compatibility of a high power arcjet system, as well as to obtain on-orbit data for comparison with ground results. The overview by Bromaghim, et al.[1] contains details of the ESEX package including a summary of the results.

Briefly, the ESEX flight system, shown in Figure 1, consists of a propellant feed system, power subsystem - including the power conditioning unit (PCU) and the silver-zinc batteries, commanding and telemetry modules, on-board diagnostics, and the arcjet assembly. The flight diagnostic suite includes thermo-electrically-cooled quartz crystal microbalance (TQCM) sensors, radiometers, antennas to detect electromagnetic interference (EMI), sample solar array cells, a video camera, and an accelerometer. ESEX was designed and built as a self-contained experiment - thermally isolated from ARGOS to minimize any effects from the arcjet firings. This design allowed ESEX to function autonomously, requiring support only for attitude control, communications,

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radiation-hardened data storage, and housekeeping power for functions such as battery charging and thermal control.

Spacecraft engineers, with the responsibility to ensure the compatibility of spacecraft systems and payloads, have questioned the EMI characteristics of arcjets. Electromagnetic signatures of low power arcjets have been studied in detail by NASA and TRW in ground tests[2,3] and a 30 kW class arcjet was ground tested in anticipation of the ESEX flight by the Air Force Research Laboratory.[4]

The impact to normal spacecraft functions and communications of operating the ESEX arcjet on-orbit were observed both quantitatively and qualitatively. On-board antennas measured electromagnetic radiation in the gigahertz range communications bands during all eight arcjet firings. Bit-error rates (BER) were measured during both arcjet firing and non-firing periods, permitting a detailed and quantitative analysis of the impact arcjet operation has ~~up~~on communications. Qualitative observations generally compared the limited event history noted from times of arcjet operation to the extensive event history recorded from all other periods of normal spacecraft operation. Observations included examining the command uplink integrity during arcjet operation and studying the telemetry downlink integrity during arcjet operation.

On-board EMI Measurements

The on-board EMI measurement system was designed to measure electromagnetic radiation emitted by the arcjet that might cause interference to the normal spacecraft functions. Though data was gathered for each of the eight firings, during quiescent

spacecraft periods, and during routine spacecraft operations, only slight, if any, variations were observed in the measured signals.

Equipment Configuration

The EMI unit measures the radio frequency (RF) noise levels received by on-board antennas and consists of an electronics processing unit, two spiral antennas, and the connecting cables, schematically shown in Figure 2. The raw antenna signal is input to the processor, where it is filtered into four frequency bands: 2, 4, 8, and 12 GHz; ± 2.5 % bandwidth. The filtered output is then amplified, converted to digital words, and serially transmitted out of the unit as telemetry to the ARGOS data recorder. The unit internally switches between the two antenna inputs such that the data is recorded one time each second overall, but in an alternating fashion at half hertz repetition rate for each antenna. The data resolution is 1 dBm/Hz with a 15 dBm/Hz dynamic range from -165 to -150 dBm/Hz.[5,6]

The two antennas are of spiral design with 2.75 inch input diameters. The deck-mounted antenna is placed on the diagnostic platform at a position in direct view of the arcjet, separated by 58 cm from the center of the antenna input to the center of the arcjet nozzle exit. The boom-mounted antenna is located at the end of a deployed boom, 138 cm from the arcjet. The positions are shown in Figure 3.

Data Acquisition

The EMI unit was activated during three classes of satellite operational conditions. For the purpose of characterizing the EMI unit behavior, data was recorded

during dormant periods of satellite activity. The EMI unit was activated during the majority of contacts between ARGOS and the controlling ground stations for the purpose of noting any responses of the EMI unit to normal spacecraft operations. Most importantly, the EMI unit was activated for all eight arcjet operations for the purpose of observing possible RF interference in the 2, 4, 8, and 12 GHz bands.

To avoid overheating of the EMI unit and maintain operational consistency, the standard procedure was to operate the EMI unit for 20 minutes each time data was recorded and to invoke the calibration routine 1 minute after EMI unit activation to confirm normal operation of the control circuitry. The same procedure for acquiring data from the on-board antennas was employed for all arcjet firing opportunities, and generally applied when data was acquired during normal spacecraft operations and during dormant spacecraft conditions. For arcjet firing opportunities, the EMI unit was powered on approximately 10 minutes prior to arcjet ignition and remained active for 20 minutes. The time ARGOS was in contact with the controlling ground station was typically 10 to 15 minutes.

Discussion

Data from the EMI unit acquired during quiescent periods serve as an appropriate baseline for comparison with data acquired during the other two classes of spacecraft activity. All of the data values from the quiescent periods are equal for both the boom- and deck-mounted antennas and are consistent at the values of -163, -164, -162, and -164 dBm/Hz for the 2, 4, 8, and 12 GHz frequency bands, respectively. Data from the periods of normal spacecraft operations are also consistent with the baseline data.

The data from the eight arcjet operation periods are shown in Figure 4, A through H, in which the ordinate has units of dBm/Hz and the abscissa denotes UTC. In general, the deck- and boom-mounted antennas register identical data values for each frequency range, with the occasional exception of the 4 GHz channel, for which the deck-mounted antenna value is often 1 dBm/Hz lower than that from the boom-mounted antenna. The step function at the bottom of the graph indicates when the arcjet is firing and the one minute gap in the data occurs during operation of the electronics calibration routine.

The data from the deck-mounted antenna obtained during the arcjet operation passes are identical to the baseline data. More importantly, the data values do not change when the arcjet fires. The data from the boom-mounted antenna obtained during the arcjet operation passes are nearly identical to the baseline data. The exception is found upon examination of the 4 and 12 GHz bands which exhibit oscillations between adjacent bits. For example, consider the data shown from the fourth arcjet firing pass (Figure 4, D), in which the indicated signal strength for the 4 and 12 GHz bands fluctuate between -164 and -163 dBm/Hz. In 5 of the 8 cases, ~~the bit-oscillations~~ occur for the 4 GHz band during the period of arcjet operation. In 3 of the 8 cases, ~~the bit oscillations occur~~ for the 12 GHz band during the period of arcjet operation. In 1 of the 8 cases, the bit oscillations occur for both the 4 and 12 GHz bands during the period of arcjet operation. Conversely, in 5 of the 8 cases, the bit oscillations frequently ~~occur~~ and in another 2 of the 8 cases, the bit oscillations infrequently ~~occur~~ for the 4 GHz band when the arcjet is not in operation. In the same 3 cases in which oscillations are observed for the 12 GHz band during arcjet operation, oscillations are also observed at times the arcjet is not operating. The digital nature of the signal processing and the 1 dBm/Hz resolution may give rise to the

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observed fluctuations in recorded RF field strength. The raw energy may oscillate in value at the decision threshold ~~value~~ between two discrete digital bits, resulting in a fluctuation in output field strength.

Caution is warranted in drawing conclusions when the instrument detects no changes. The trivial explanation of malfunctioning equipment, and therefore no recorded signal changes must be addressed prior to discussing the meaning of the data. The ideal test would have been to irradiate the on-board antennas from the ground with a known signal intensity (at the antennas) to not only verify proper operation but to also calibrate the measurement; however, circumstances prevented this test from being conducted. Alternatively, the EMI unit response to invoking the internal calibration routine may be examined. In all cases the internal calibration results were consistent with proper signal processing behavior.

on-ground

If the EMI detection equipment functioned as designed, the data suggest that operation of the 26 kW ESEX arcjet does not adversely interfere with the 2, 4, 8, and 12 GHz communication bands. This is consistent with the ground test observations, in which measured RF signals caused by arcjet operation exceeded ambient levels only over the frequency range of 10 kHz to 5 MHz.[4]

Bit-Error Rate Test

The BER test enabled a quantitative study of the effect operating the ESEX arcjet had upon S-band communications. Control of ARGOS is accomplished via the satellite ground link system (SGLS) architecture, which operates over a number of S-band

channels near 2 GHz. ARGOS SGLS communications include encrypted command and telemetry channels, as well as an unencrypted dedicated ranging channel used for orbit determination. Typically, to determine the range to the satellite, a pseudo-random noise (PRN) signal pattern is transmitted from a ground site of the Air Force Satellite Control Network (AFSCN) to the spacecraft, which in turn frequency-shifts the signal and retransmits the code back to the ground site. Synchronization of the PRN code is used to determine the time delay, which is used for range determinations. The return carrier is either offset from the uplink carrier by a specific delta-frequency (coherent mode) or is established independently from the uplink by a spacecraft reference (incoherent mode). The coherent mode is used to obtain range rate (velocity) measurements from Doppler frequency shifts. The BER test utilizes the SGLS range channel, but replaces the PRN ranging code with a 2048-bit error-counting code. The transmitted bit pattern is compared with the received bit pattern and the bit-error rate is quantitatively measured.

Test Equipment, Configuration and Procedure

The BER test was conducted at the Camp Parks Communication Annex (CPCA) and testing was coordinated with the RDT&E Support Complex (RSC) controlling ARGOS at the USAF Space and Missile Test and Evaluation Directorate, Kirtland AFB, NM. A schematic of the BER test activities is presented in Figure 5. The ARGOS SGLS transponder is activated prior to satellite rise, broadcasting an S-band signal locked to the on-board frequency standard. The remote tracking station (RTS) receives and locks to the signal, establishing two-way communication. When normal commanding and data downloading is complete, the RSC directs the RTS to drop the active link (cease

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transmitting) and then the CPCA is directed to initiate the BER test, functioning in incoherent mode.

The Fireberd 6000 generates a 2048 bit pattern (in place of the PRN bit pattern), output to the signal modulator. The signal, with a modulation index of 0.6 radians, is combined with the carrier frequency (2.2655 GHz) and passed through the high power amplifier, transmitter and 10 m antenna. The satellite transponder demodulates the signal and immediately modulates the downlink carrier frequency (1.811768 GHz) with the 2048 bit pattern. Because the process bypasses encryption, the measured BER accurately represents the number of errors incurred in the communication cycle. The signal is received by the 10 m antenna, passes through the receiver and amplifier on the way to the Fireberd 6000. The received 2048 bit pattern is compared with the original pattern and the number of errors is counted and output to a computer (See Figure 6).

The transmission rate was 1.024 Mbps and the combination of CPCA transmitter power and modulation index were set such that about 10 errors per second (1 error in 10^5) were generated when the satellite slant range was at a minimum. This effectively maximized the BER test sensitivity by adjusting the error threshold. Typically, 1 error in 10^6 is considered acceptable in normal communication circuits. It is important to note that a near zero error rate could be obtained for any given BER test by increasing the transmitter power or by setting an appropriate modulation index.

The BER test in this configuration was proven in a trial with MSTI-3, among other USAF SGLS capable satellites, and was successfully employed throughout the ESEX program for a variety of test conditions.[7] The 2048 bit pattern was designed to emulate normal data bit patterns and thereby avoids signal resonances that can be

established in the electronic equipment for cases in which the bit pattern period is too short, e.g. 010101. The Fireberd 6000 generates the code and compares the transmitted and received patterns, recording the number of bit-errors per second.

The CPCA in Dublin, California served as the ground station for all BER tests. The 10 meter parabolic, prime focus antenna has an uplink gain of 39.6 dB, a downlink gain of 23.6 dB, a beam width of 1°, and a slew rate of 6 degrees per second.[8]

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The BER for a fixed modulation is observed to be extremely sensitive to transmitter output power. A 1 dB reduction in uplink power corresponds to about a factor of two increase in measured BER at the minimum slant range point in the satellite pass. The high power amplifier used for the ESEX BER tests is of class C type (maximum amplitude stability at full output power is about 200 W.) The amplitude drift after 1 hour of continuous operation at full transmit power was stable to within a few tenths of a dB. Operation at a reduced transmit power caused amplitude drifts of several dB for the first 20 minutes of operation. For a reduction in power by 3 dB, after 1 hour of continuous operation, the drift was slightly more than 1 dB over 10 minutes. The majority of BER test data was obtained with an output power of 200 W; however, the first two arcjet firing BER tests were conducted with an output power of 100 W.

Data Analysis and Discussion

Satellites in polar orbits track across the sky, rising to a maximum elevation and then setting below the horizon either east or west of the ground station. In the case of ARGOS, all BER tests were conducted such that the satellite rose in the south and set toward the north of the CPCA. BER testing could begin as early as a rising elevation of 3

degrees, corresponding to a slant range of nearly 3700 km. Correspondingly, BER testing could be sustained as late as a setting elevation of 3 degrees. Maximum elevations greater than 85 degrees generally present difficulties in SGLS tracking, known as the keyhole effect. For the ARGOS orbit, an elevation of 90 degrees corresponds to a slant range of 850 km ~~and~~ continuous tracking of the satellite for overhead passes was troublesome because the CPCA 10 m antenna drive mechanism was not fast enough to rotate the dish to maintain proper EM wave polarization and sustain SGLS communication signal lock. Fortunately, it was a rare occasion that the maximum elevation was greater than 85 degrees during the ESEX BER test opportunities.

An example of BER test data is shown in Figure 7, in which several issues related to this type of test are illustrated. The bit-error rate is proportional to slant range, primarily due to atmospheric absorption of the 2 GHz carrier signal strength. The ordinate shows the number of bit-errors counted per second and the abscissa shows the slant range, defined as the line-of-sight distance from the CPCA antenna to the ARGOS SGLS antenna. For convenience, negative slant ranges are defined as the rising portion of the satellite orbit (elevations increasing with time) and positive slant ranges are defined as the setting portion of the orbit (elevations decreasing with time.)

The rising BER data in Figure 7 was recorded with a modulation index of 0.6 radians and a transmitter power of ~~a~~ 200 W. The measured BER decreases from nearly 500 bit-errors per second to less than 50 near the minimum slant range of 1300 km. The curve is smooth because the output transmitter power was stable to within 5 %. In contrast, the BER curve for the setting half of the pass is discontinuous with an increase in measured errors because the transmitter power was reduced by 12 dB, drifted, and was

periodically reset. The variation in transmitted power was verified by examining the on-board antenna receiver signal strength data. The transmitted power fluctuated because the class C amplifier had not stabilized and the BER is sensitive to transmitter power. For example, the transmitter power was set to 20 W at the minimum slant range and had drifted toward lower powers. At the setting slant range of 1575 km, the transmitter power was abruptly reset to 20 W, reducing the BER from 479 to 242 bit-errors per second. A 0.8 dB increase in transmitter power corresponded to a factor of 2 decrease in measured BER, denoting the sensitivity of the BER test to transmitter power. The transmitter power was adjusted again at a setting slant range of 1850 km with a corresponding reduction in BER. The transmitter power was allowed to continue drifting toward lower power at a slant range of 2150 km, giving rise to the bend in the BER curve. It should be noted that using a class A amplifier would stabilize the transmitted power and provide improved BER test results.

The data indicated by 0 bit-errors per second on the rising half of the BER curve shown in Figure 7 represent moments when the Fireberd 6000 experienced momentary loss of synchronization with the bit stream, termed sync loss. Sync losses are spurious artifacts of the test configuration and occur when the measured bit-error rate is near zero but the synchronization bit happens to be the bit in error. Thus, for maximum test sensitivity the goal is to adjust the mod index and transmitter power such that at maximum elevation the number of errors is small but quantifiable and sync losses are uncommon. The individual data points above the average BER values occur without regular frequency and are not obviously correlated to any of the test parameters.

To fully characterize the novel BER test, more than 45 sets of data were acquired for a wide variety of experimental conditions. Figure 8 is a composite of 38 BER curves, with the example data from Figure 7 shown in black and the rest of the data shown in grey. The increase in BER at the minimum slant ranges is due to the keyhole effect. The BER data with errors greater than 300 for slant ranges less than about 2500 km correspond to passes in which the transmitter power was set less than 100 W. The majority of baseline BER data were obtained with a transmitter power of 200 W and the data typically reflect less than 200 bit-errors per second at a transmitted rate of 1024 kbps (200 errors per 10^6 bits).

Arcjet Firing # 2 BER Test

The BER curves shown in Figure 9 are related to arcjet firing # 2. The two curves were obtained on sequential passes, with a fixed modulation index of 0.6 radians and a constant transmitter power of 100 W, stabilized by operating the transmitter into a dummy load for an hour prior to BER testing. The unadjusted transmitter output power drifted to lower power by about 1 dB during both passes. The first pass followed an easterly track, represented by open circles in Figure 9, with a maximum elevation of 29°, a minimum slant range of 1490 km, and serves as a baseline condition because the arcjet was not firing during this pass. The next orbital revolution followed a westerly track, represented by closed circles, with a maximum elevation of 33°, a minimum slant range of 1370 km, and the arcjet was continuously firing for the entire duration of the BER test.

The BER curve from the baseline segment closely overlaps that portion of the BER curve from the arcjet firing for slant ranges between 1750 km and 1950 km,

beginning to diverge slightly as slant range increases. That portion of the BER curve from the arcjet firing for slant ranges between 1530 km and 1645 km show numerous sync losses and relatively high bit-error rates. Though it is not possible to draw a conclusion regarding the influence of arcjet operation upon measuring the bit-error rate based solely upon the data shown in Figure 9, some discussion may be useful. The same behavior of a sudden, temporary increase in measured bit-error rate with a simultaneous increase in sync loss frequency has been observed in several BER tests conducted during periods when the arcjet was not operating, as can be seen in Figure 8. Though the transmitter power was not recorded as a function of time during each BER test to verify the following behavior, it has been observed that the power could drift in such a way that sync losses are promoted with a corresponding increase in BER.

If the operation of the ESEX arcjet adversely influenced SGLS communications, the BER test would be sensitive to the increased number of errors. It is unlikely that the arcjet would introduce errors sporadically, rather it is expected that the interference from arcjet operation would be continuous. The observed increase in BER followed by recovery to overlap the baseline BER curve suggests an error source related to the test equipment. It should be noted that even if operation of the ESEX arcjet did cause the increase in observed BER, that increasing the transmitter power from 100 W to 200 W would probably reduce the bit-error rate to within acceptable tolerances.

Arcjet Firing # 4 BER Test

The BER curve obtained during arcjet firing # 4, a representative baseline BER curve, and the arcjet power are shown in Figure 10, represented by closed circles, open

circles, and a line, respectively. For the BER curve obtained during arcjet firing # 4, the transmitter power was 100 W and the easterly orbit had a maximum elevation of 67° with a minimum slant range of 920 km. For the baseline BER curve, the transmitter power was 200 W and the westerly orbit had a maximum elevation of 47° with a minimum slant range of 1080km. For both BER curves, the modulation index was 0.6 radians.

Two features of the BER curve obtained during arcjet firing # 4 are apparent. The number of bit-errors per second decreases sharply at a slant range of 2115 km and the sync losses occur for slant ranges less than 2071 km. The arcjet was ignited prior to beginning the BER test and the arcjet turned off at a time corresponding to a slant range of 2185 km, as indicated by the arcjet power trace shown in Figure 10. The difference between the time the arcjet turned off and the time the bit-error rate sharply decreased is 9 seconds with an uncertainty of 1 second. The BER test data was time-stamped by the Fireberd 6000 and was adjusted forward by 1 second to synchronize with UTC. The ESEX telemetry used to calculate the arcjet power trace was time-stamped by the ESEX clock and was adjusted such that the maximum error between UTC and the ESEX clock was 1 second. Given that the arcjet shut off 9 seconds after the qualitative change in the BER curve appearance, and that the arcjet power trace is approximately constant, it is unlikely that operation of the ESEX arcjet caused the increase in sync losses and measured BER.

The cause of the qualitative change in appearance of the arcjet BER data is unresolved; however, some discussion is warranted. Some BER test data have features in common with the arcjet BER data. For example, when intentional and abrupt changes in transmitter power are made, the measured bit-error rate immediately reflects the change

and sync losses are common when the transmitter power is low. A sudden increase in transmitter power is consistent with the shift in the arcjet BER data.

The baseline BER data was obtained at a fixed power of 200 W and is compared with the arcjet BER data. The baseline and arcjet BER data precisely overlap for slant ranges greater than 2115 km, which would be consistent if the transmitter power was 200 W during the arcjet BER test. The average measured bit-error rate of the arcjet BER data is about 4 times larger than that of the baseline BER data for slant ranges between 1500 km and 2000 km, which is consistent with expectations based upon empirical observations of the effect changing the transmitter power from 200 W to 100 W has on the measured BER.

It should also be mentioned that telemetry dropouts were experienced by the RTS during the same time period that the BER test experienced sync losses. Telemetry dropouts occur when the data transmitted from ARGOS to the ground station are corrupted, and such dropouts were experienced during many contacts in which the arcjet was not operated.

Arcjet Firing # 7 BER Test

In an effort to avoid sync losses, the transmitter power was set to 200 W for the BER test that was conducted during arcjet firing # 7, shown in Figure 11. The modulation index was set to 0.6 radians and the westerly pass had a maximum elevation of 53° with a minimum slant range of 1020 km. The single BER test was initiated prior to arcjet ignition, continuously conducted during arcjet operation, and terminated after

arcjet shutdown. The open and closed circles represent BER test data for times the arcjet was off and on, respectively.

Arcjet firing # 7 experienced some difficulty in which the arcjet ignited and shut off twice. The first period of arcjet operation coincides with rising slant ranges between 1200 km and 1436 km and appears to have no more bit-errors per second than the trend indicated by the prior time. The second period of arcjet operation coincides with rising slant ranges between 1055 km and 1160 km and may have a slightly increased bit-error rate. This increased BER may be because the power conditioning unit was operating tens of volts below specification and may have been generating noise. Additional discussion of this anomaly is presented by D.R. Bromaghim.[1]

In summary, three arcjet firings and thirty-eight baseline BER curves were recorded during the ESEX flight, shown together in Figure 12, with the arcjet firings highlighted by black dots. No clear correlation between features observed in the arcjet firing BER data and the operation of the arcjet has been identified.

Qualitative Observations

The impact of arcjet operation on standard spacecraft function was studied by comparing event behavior during times of arcjet operation to normal behavior patterns.

The integrity of the uplink was studied by transmitting commands to ARGOS while the arcjet was operating. The command acceptance rate was noted and compared to the extensive database of typical command acceptance rates. In none of the 8 arcjet firing operations was the command rejection rate atypical.

The integrity of the telemetry downlink was studied during arcjet operation. A known bit pattern was stored to the ARGOS recorder and then downlinked several times. The transmitted test patterns from periods when the arcjet was not operating were compared with test patterns transmitted during times of arcjet operation and differences were noted. In none of the comparisons were the number of errors larger than tolerances allow. Consider for example data from orbit revolution 369.4, in which arcjet firing # 3 occurred. The test pattern was transmitted once prior to arcjet ignition as a control, once such that the arcjet ignition occurred in the middle of the test pattern transmission, once such that the arcjet was continuously on during the test pattern transmission, and once such that the arcjet shutoff in the middle of the test pattern transmission. Out of the 8,688,161 byte test pattern, less than 4 errors were noted between the control transmission and transmissions during arcjet operation.

The telemetry dropout rate tended to be larger than anticipated for general ARGOS operation Some of the arcjet operations coincided with significant loss of telemetry; however, numerous ARGOS contacts in which the arcjet was not operating also experienced extreme telemetry dropouts. Examination of the dropout patterns for periods when the arcjet was on and off did not reveal any correlation between dropouts and arcjet operation. For example, during arcjet firing # 1 there were no telemetry dropouts. Arcjet firing # 2 had dropouts before, during, and after arcjet operation. During arcjet firing # 4, dropouts occurred only when the arcjet was firing. During arcjet firing # 7, the dropouts happened before and after, but not during the arcjet operation.

Conclusions

The test objective to perform an assessment of the electromagnetic impact of operating the ESEX 26 kW arcjet was achieved. No indication that the arcjet adversely affects normal spacecraft communications and operations was clearly identified. Signals from the on-board antennas show no effect from arcjet operations on the typical communications bands. While the BER data possibly show a measurable effect from arcjet operations, the impact to future space systems is likely to be small. The 30 kW class arcjet operated satisfactorily in the space environment and the on-board antennas did not register data values that differed from firing to non-firing periods, suggesting low EMI arcjet output at the measured frequencies. The BER curves from arcjet firing and non-firing periods differ slightly, but no clear correlation between the BER data and arcjet operation was identified. Commands uplinked without abnormal rejection rates and telemetry downlinked successfully during arcjet operation and it is unlikely that operation of a 30 kW class arcjet will adversely affect normal spacecraft communications.

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Not a reference because the Reader cannot look it up. Make this a footnote instead. Same for Ref. 7

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References #6 + #7: may be used as footnotes...
references should be material available for someone to look up / research

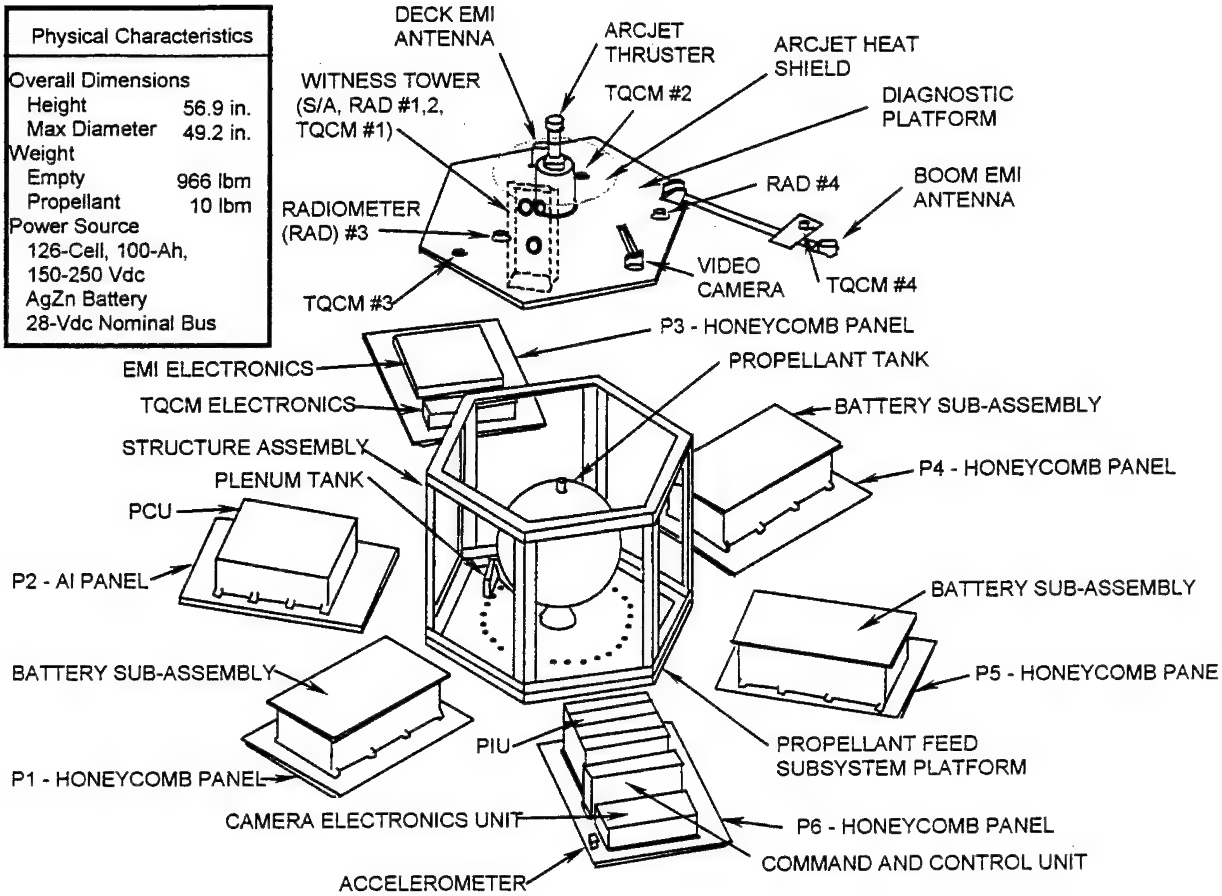


Figure 1 - Exploded view of the ESEX flight unit

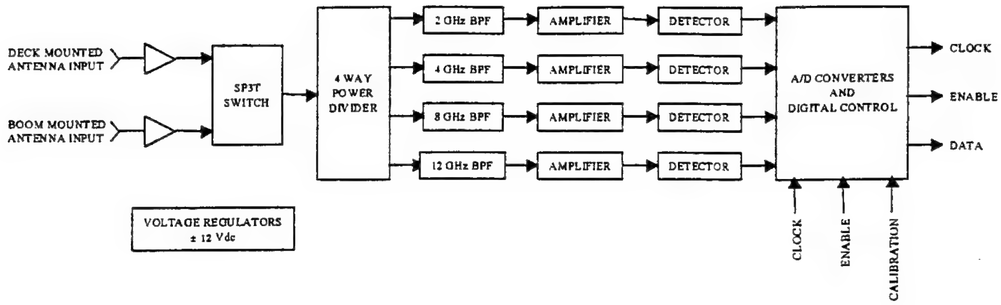


Figure 2 - EMI Experiment Block Diagram

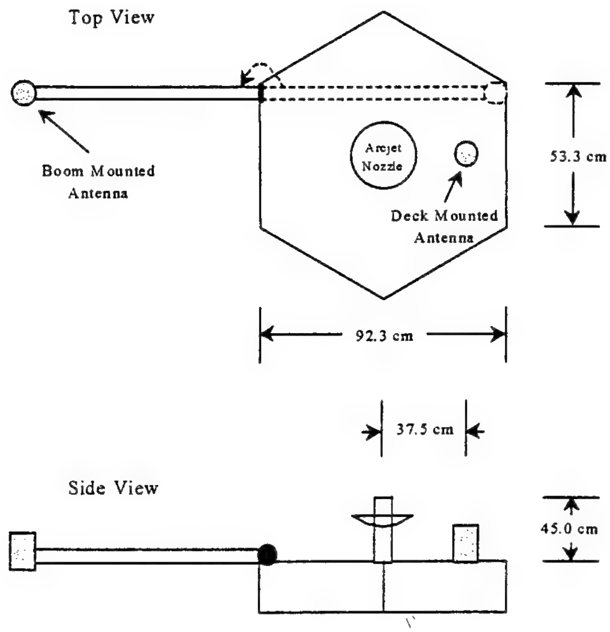


Figure 3 - Antenna Positions

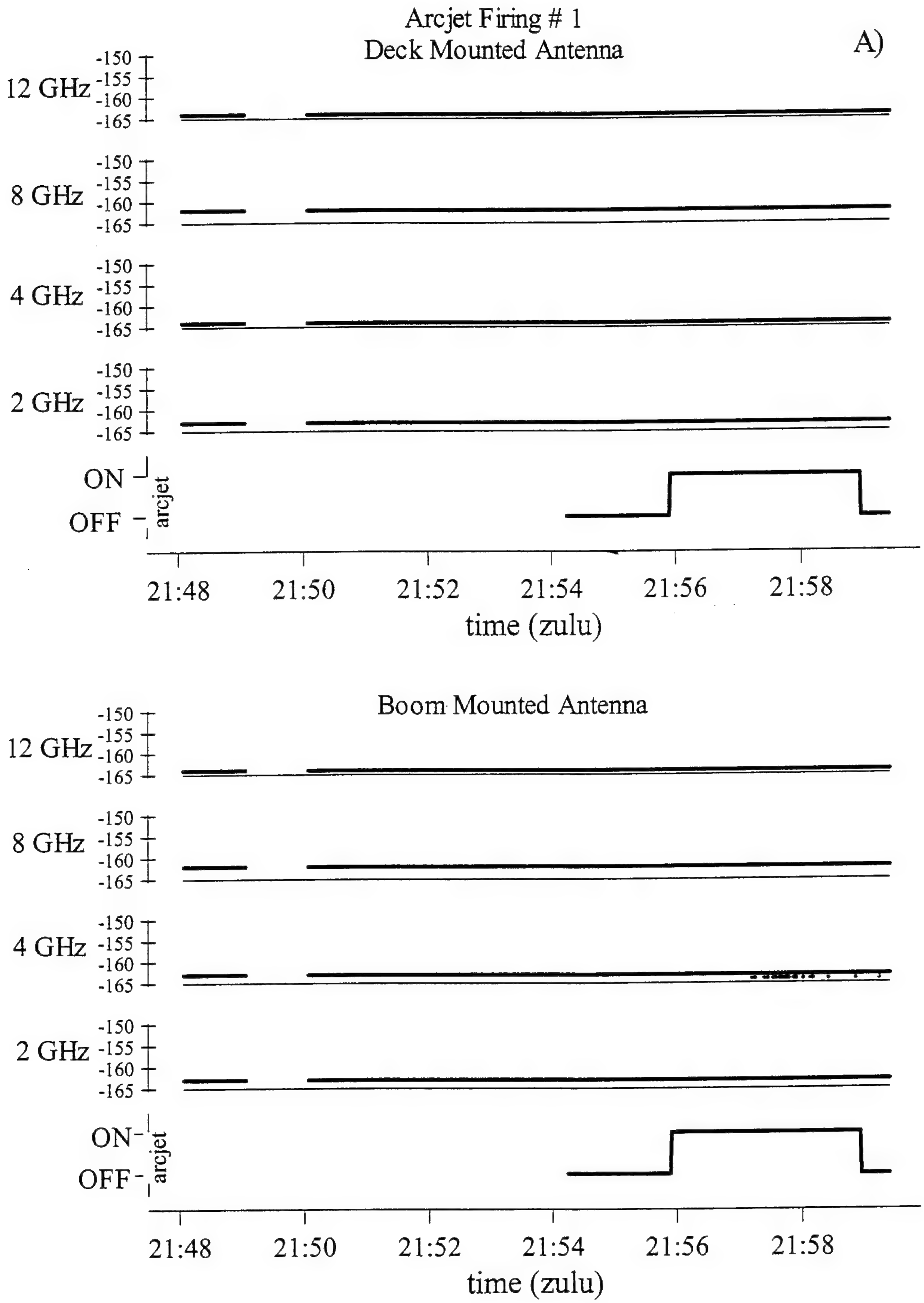
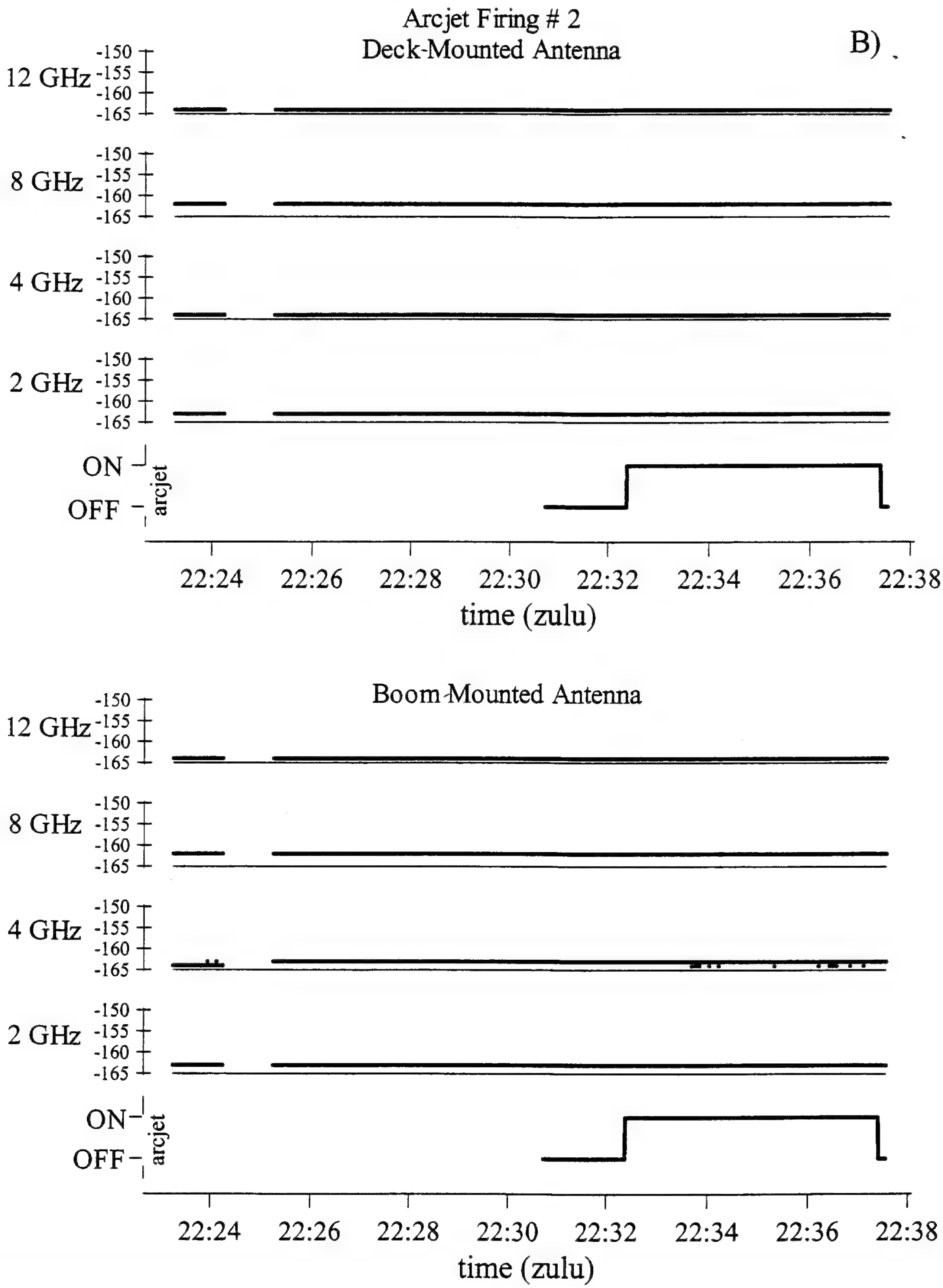
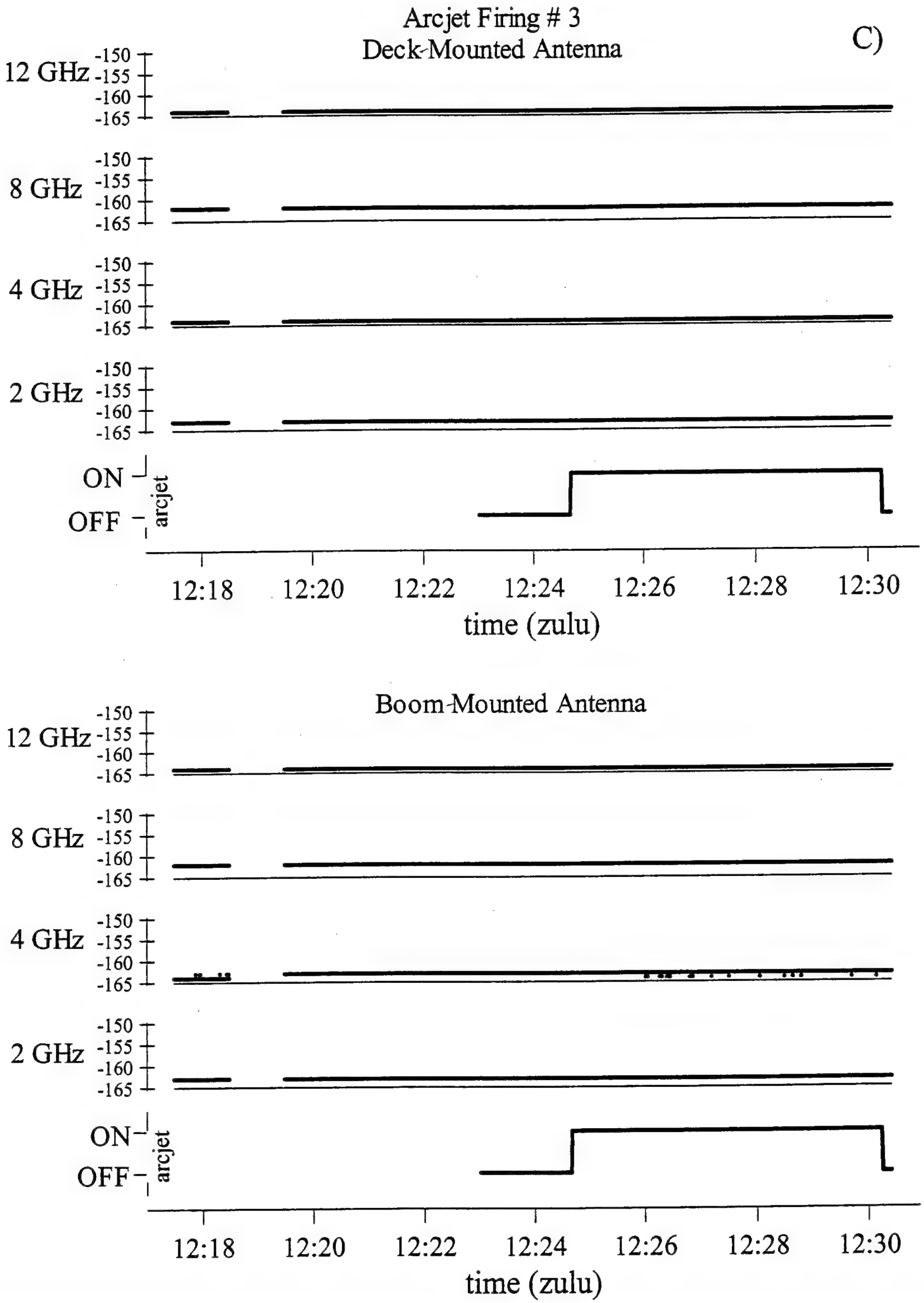


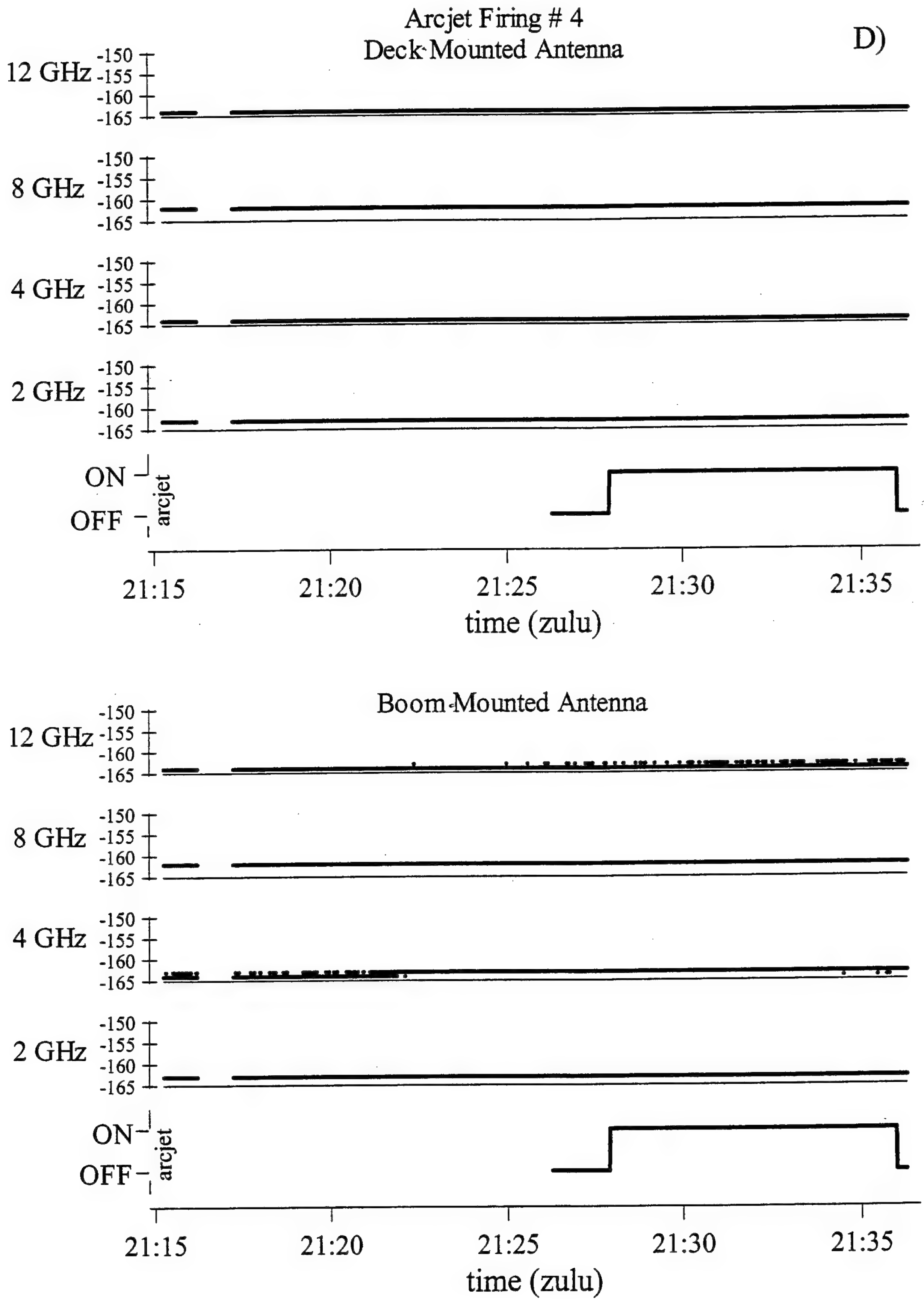
Figure 4 Title/caption?


Arcjet Firing # 2
Deck-Mounted Antenna
B)
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
22:24
22:26
22:28
22:30
22:32
22:34
22:36
22:38
time (zulu)
Boom-Mounted Antenna
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
22:24
22:26
22:28
22:30
22:32
22:34
22:36
22:38
time (zulu)



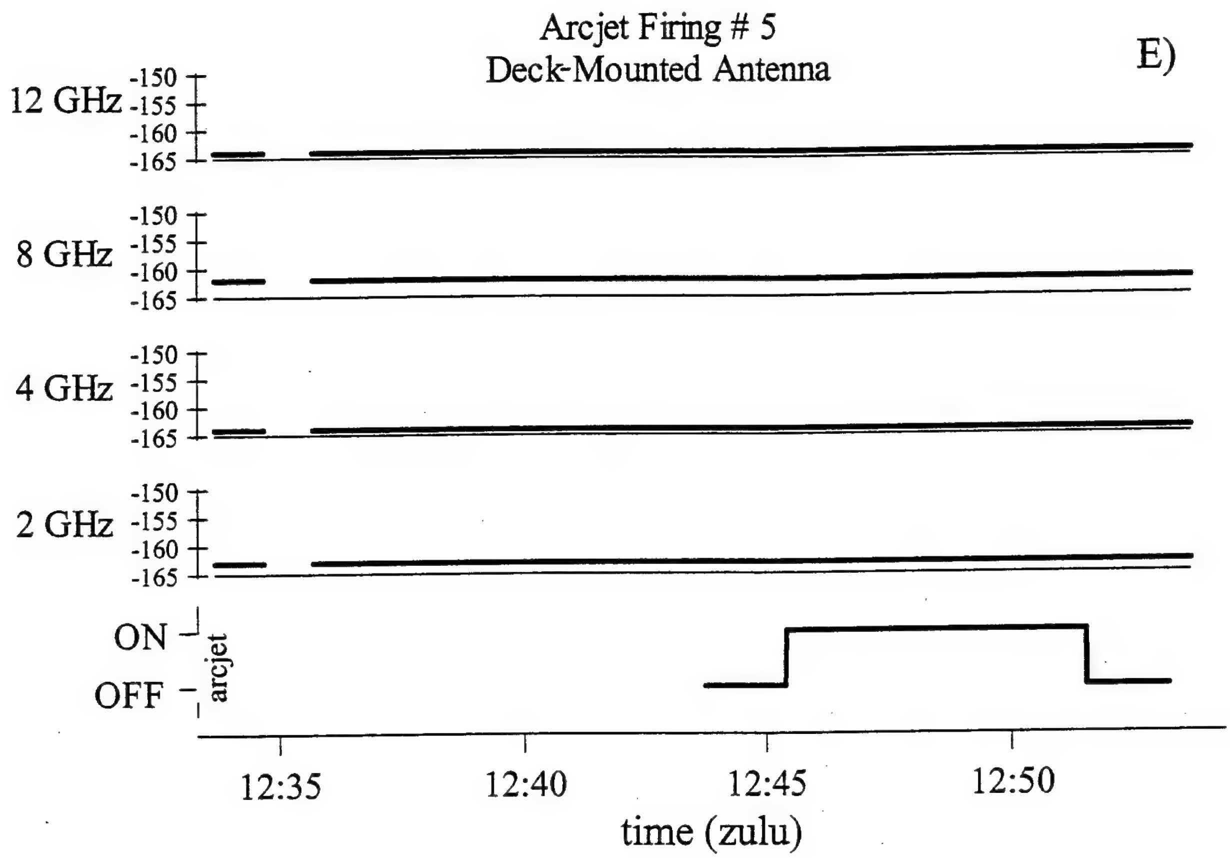
Arcjet Firing # 3
Deck-Mounted Antenna
C)
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
12:18
12:20
12:22
12:24
12:26
12:28
12:30
time (zulu)
Boom-Mounted Antenna

Figure 4

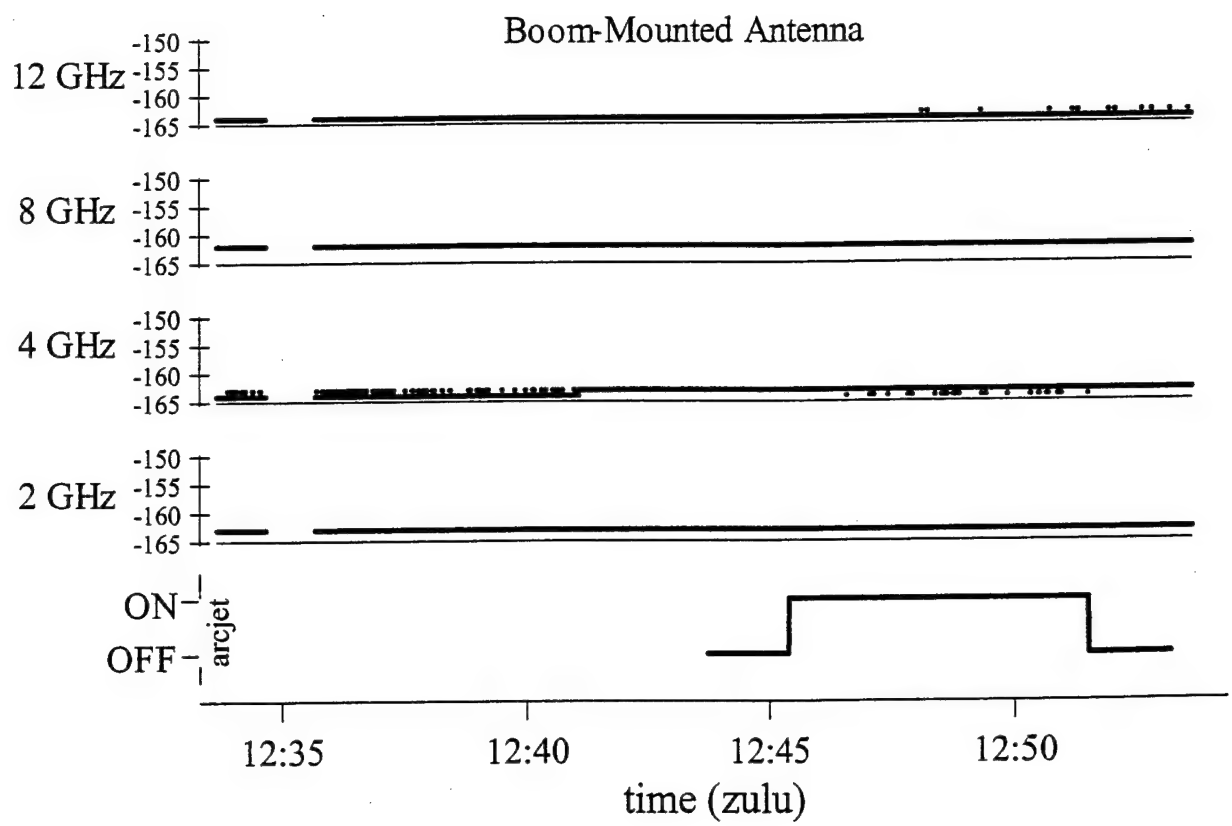


Arcjet Firing # 4
Deck-Mounted Antenna
D)
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
21:15
21:20
21:25
21:30
21:35
time (zulu)
Boom-Mounted Antenna

Figure 4



Arcjet Firing # 5
Deck-Mounted Antenna
E)
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
12:35
12:40
12:45
12:50
time (zulu)



Boom-Mounted Antenna
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
12:35
12:40
12:45
12:50
time (zulu)

Figure 4

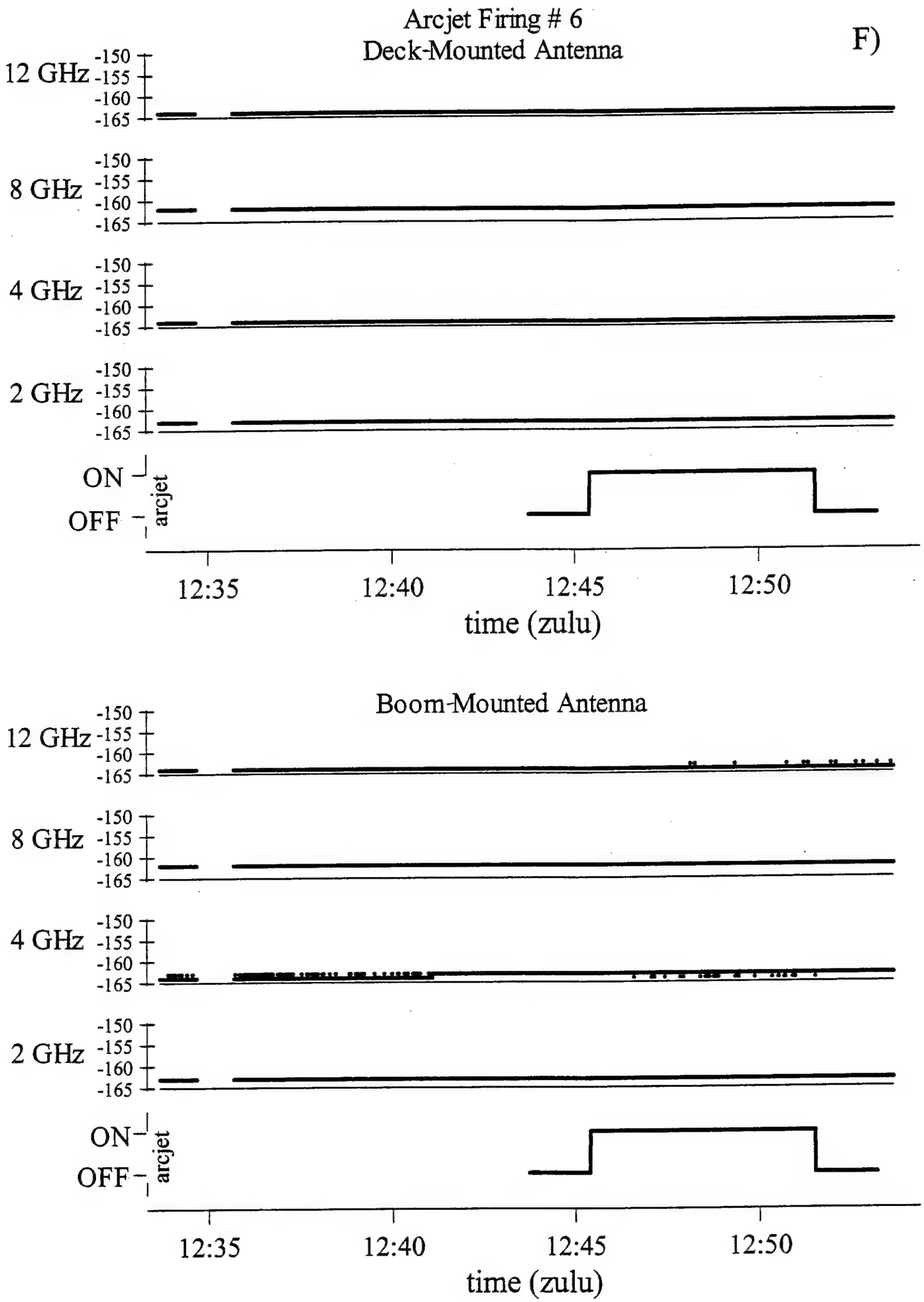

Arcjet Firing # 6
Deck-Mounted Antenna
F)
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
12:35
12:40
12:45
12:50
time (zulu)
Boom-Mounted Antenna

Figure 4

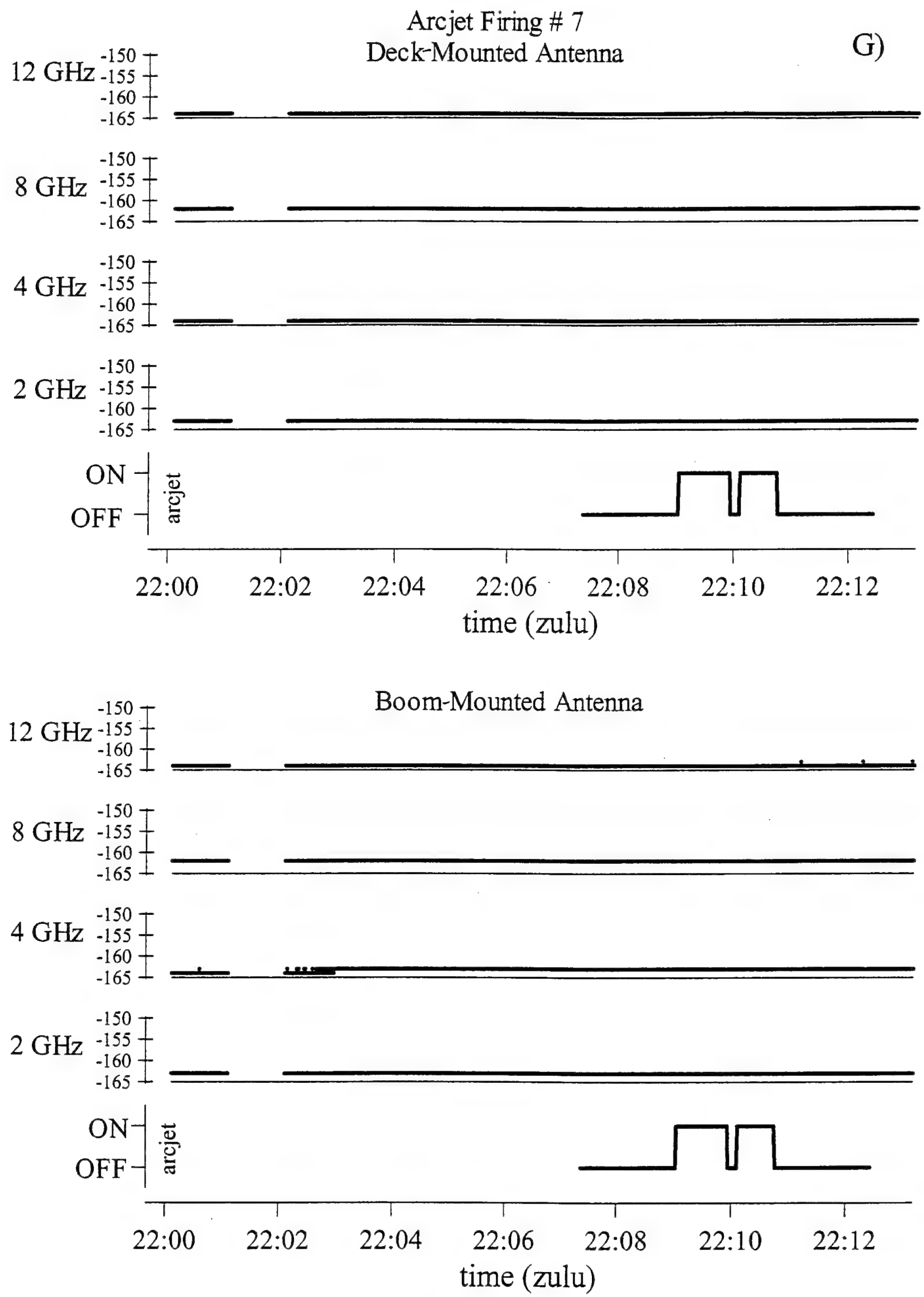

Arcjet Firing # 7
G)
Deck-Mounted Antenna
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
22:00
22:02
22:04
22:06
22:08
22:10
22:12
time (zulu)
Boom-Mounted Antenna

Figure 4

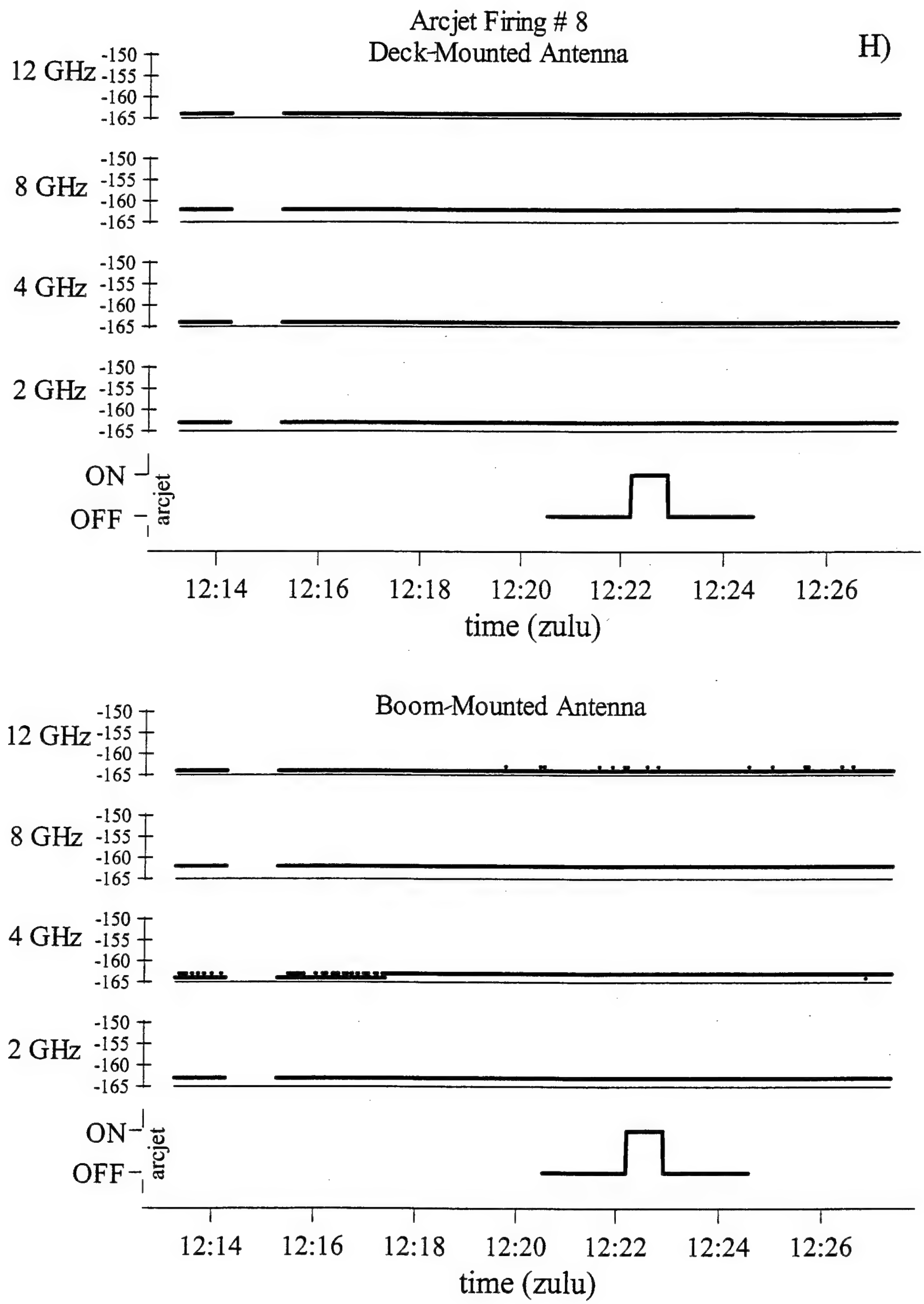

Arcjet Firing # 8
Deck-Mounted Antenna
H)
12 GHz
8 GHz
4 GHz
2 GHz
-150
-155
-160
-165
ON
OFF
arcjet
12:14
12:16
12:18
12:20
12:22
12:24
12:26
time (zulu)
Boom-Mounted Antenna

Figure 4

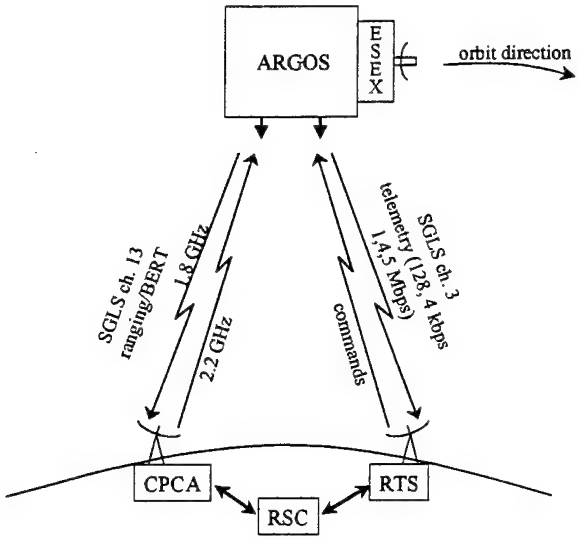


Figure 5 - Overview of BER Test Assets: Advanced Research and Global Observation Satellite (ARGOS); Electric Propulsion Space Experiment (ESEX); Satellite Ground Link System (SGLS); Camp Parks Communication Annex (CPCA); Remote Tracking Station (RTS); RDT&E Support Complex (RSC)

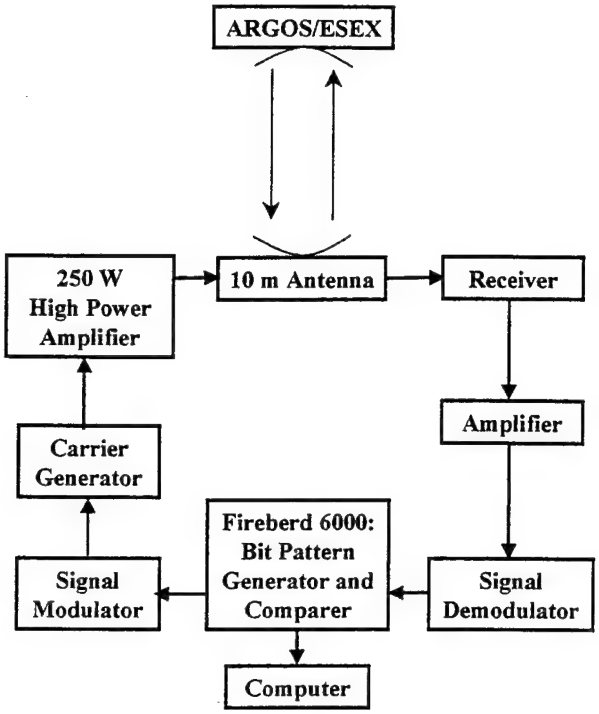


Figure 6 - BER Test Communication Circuit

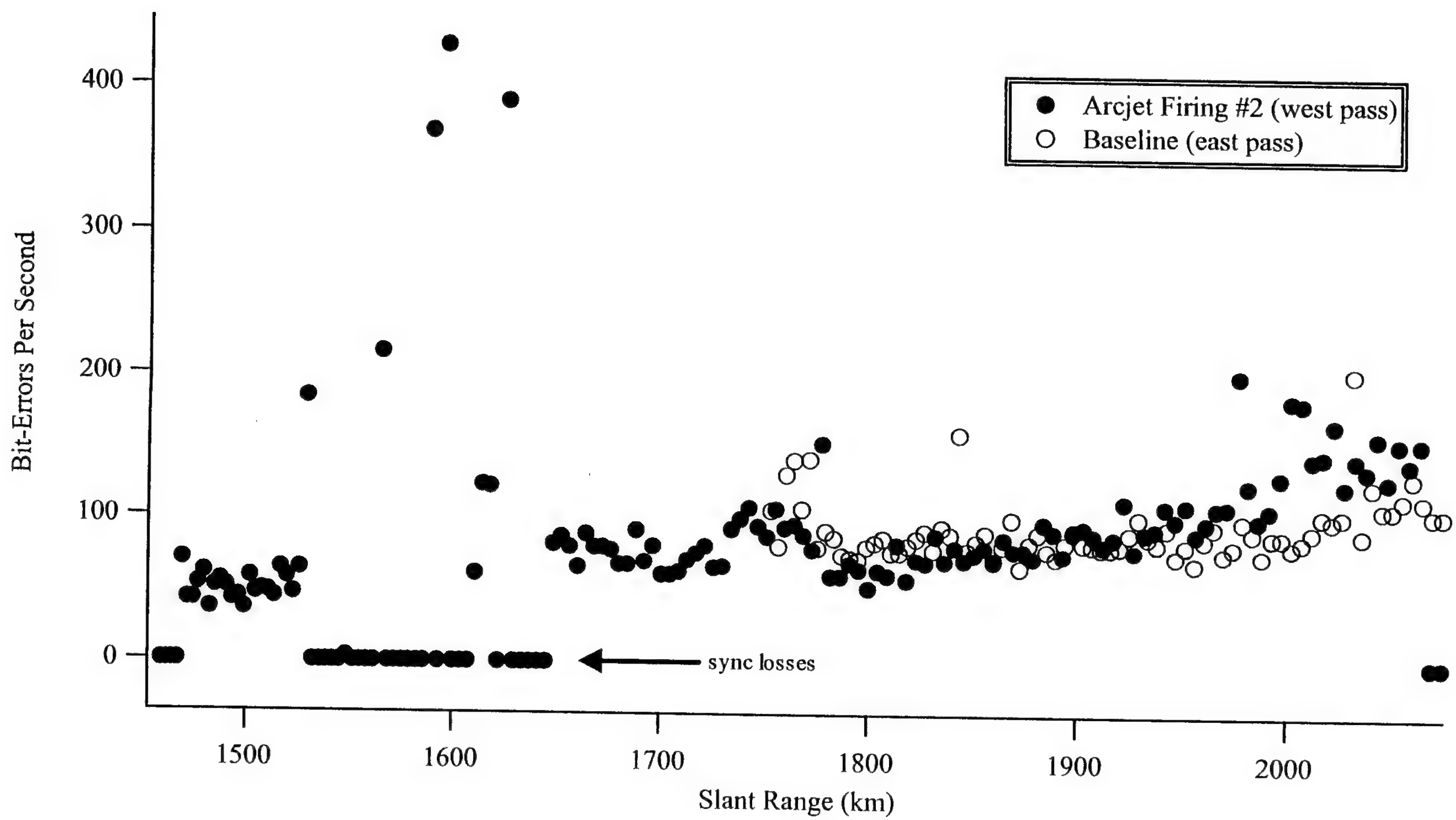


Figure 9 - Arcjet Firing # 2 BER Test

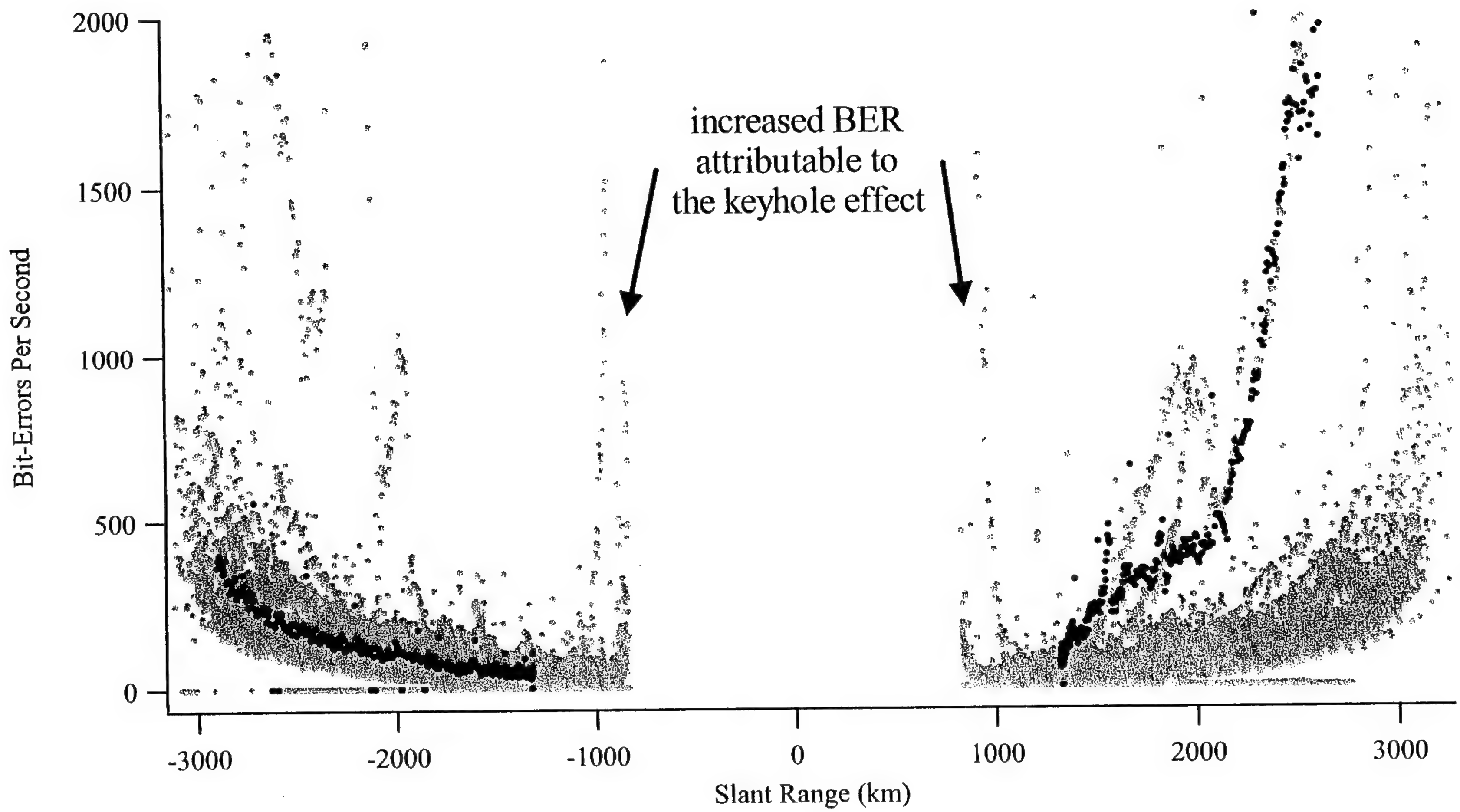


Figure 8 - Composite of 38 BER Test Results with data from Figure 7 shown by black dots

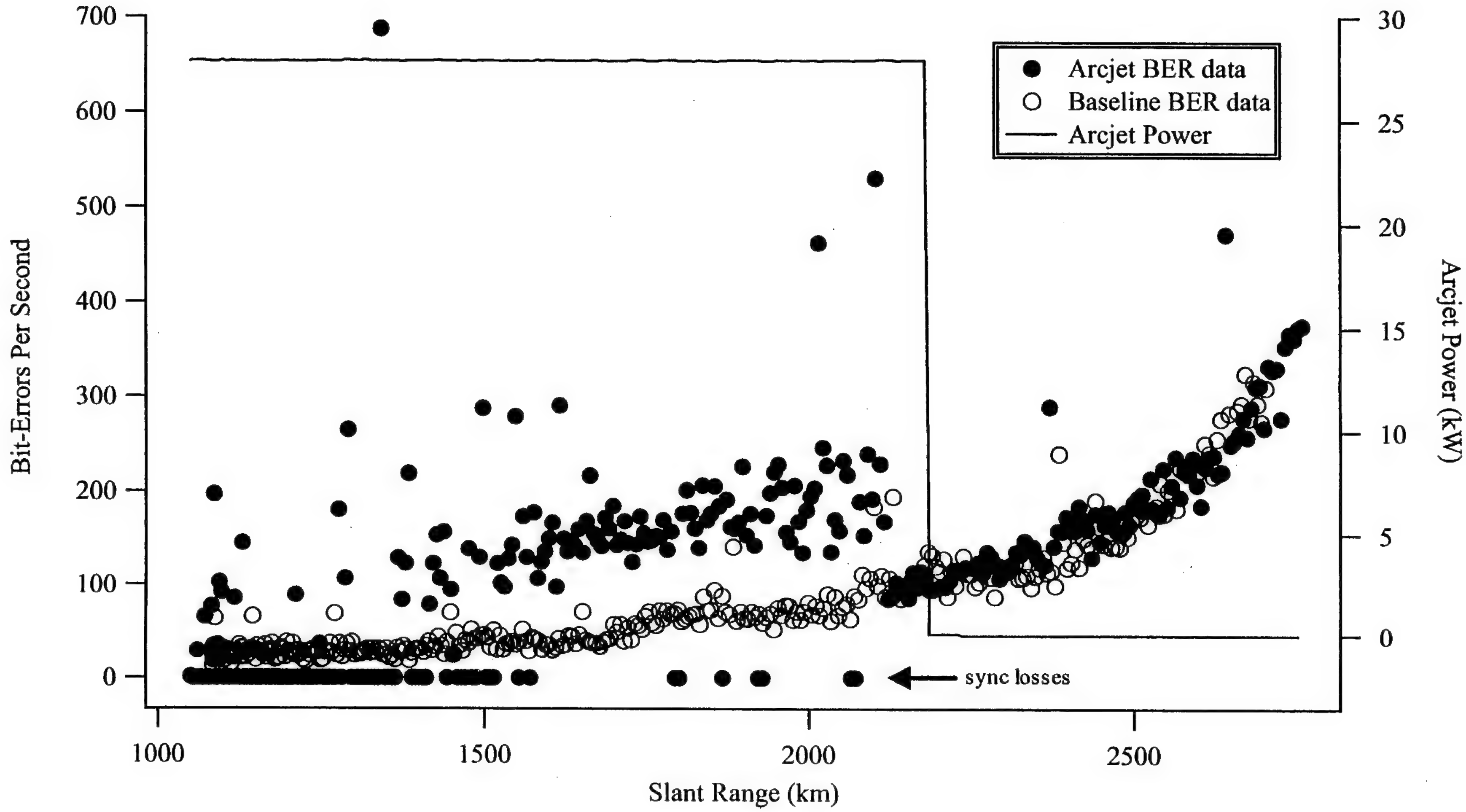


Figure 10 - Arcjet Firing # 4 BER Test

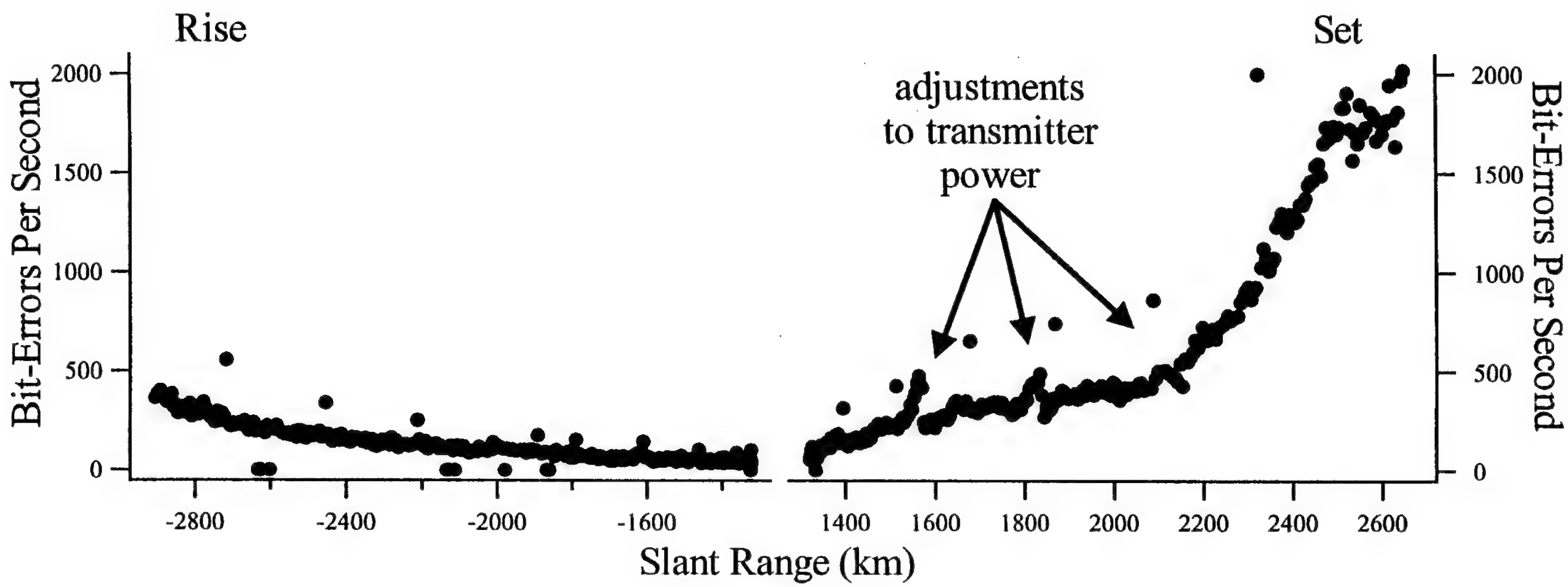


Figure 7 - Representative BER Test Data. Negative slant range is defined as the rising portion of the satellite orbit; positive slant range is defined as the setting portion of the satellite oribt.

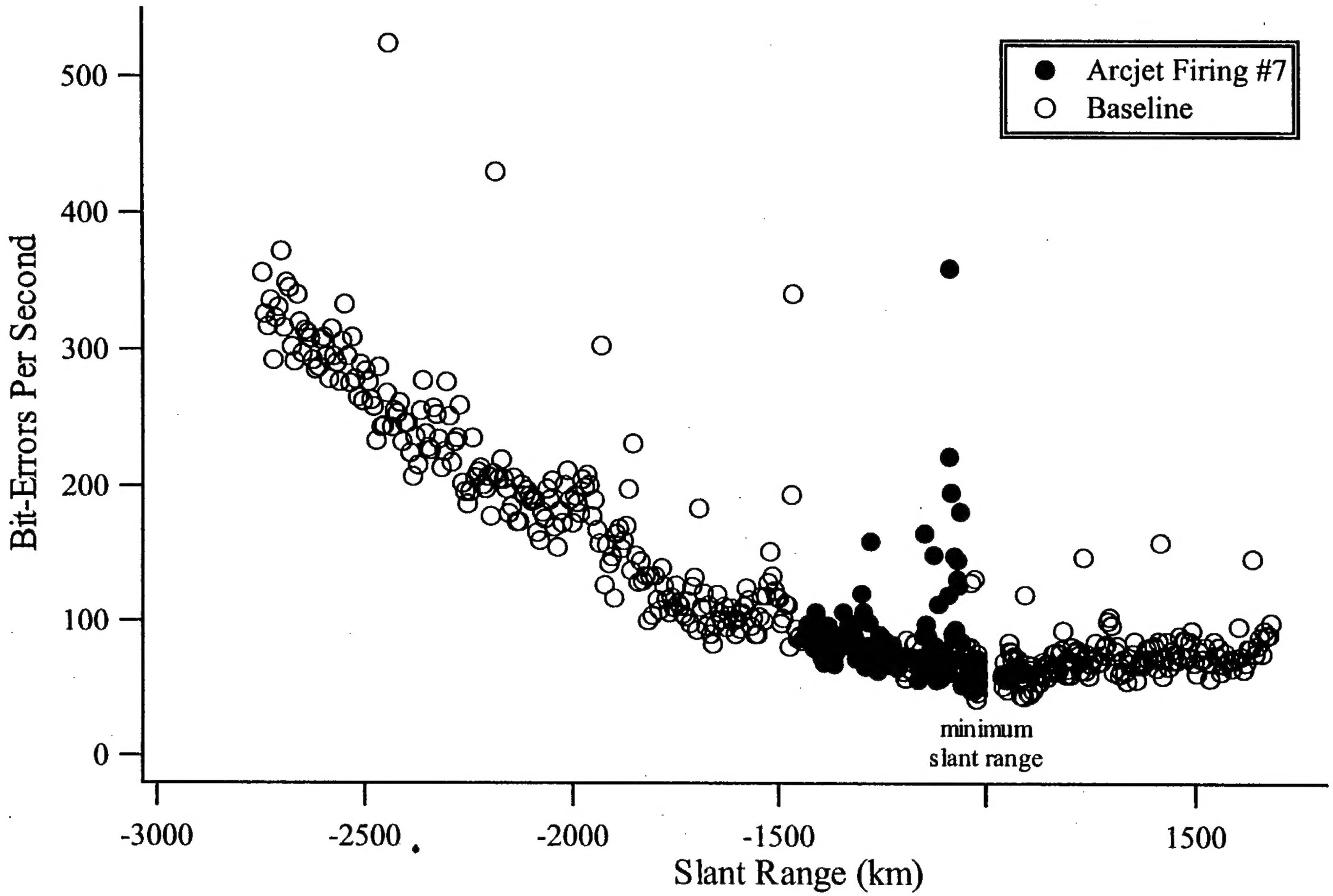


Figure 11 - Arcjet Firing # 7 BER Test

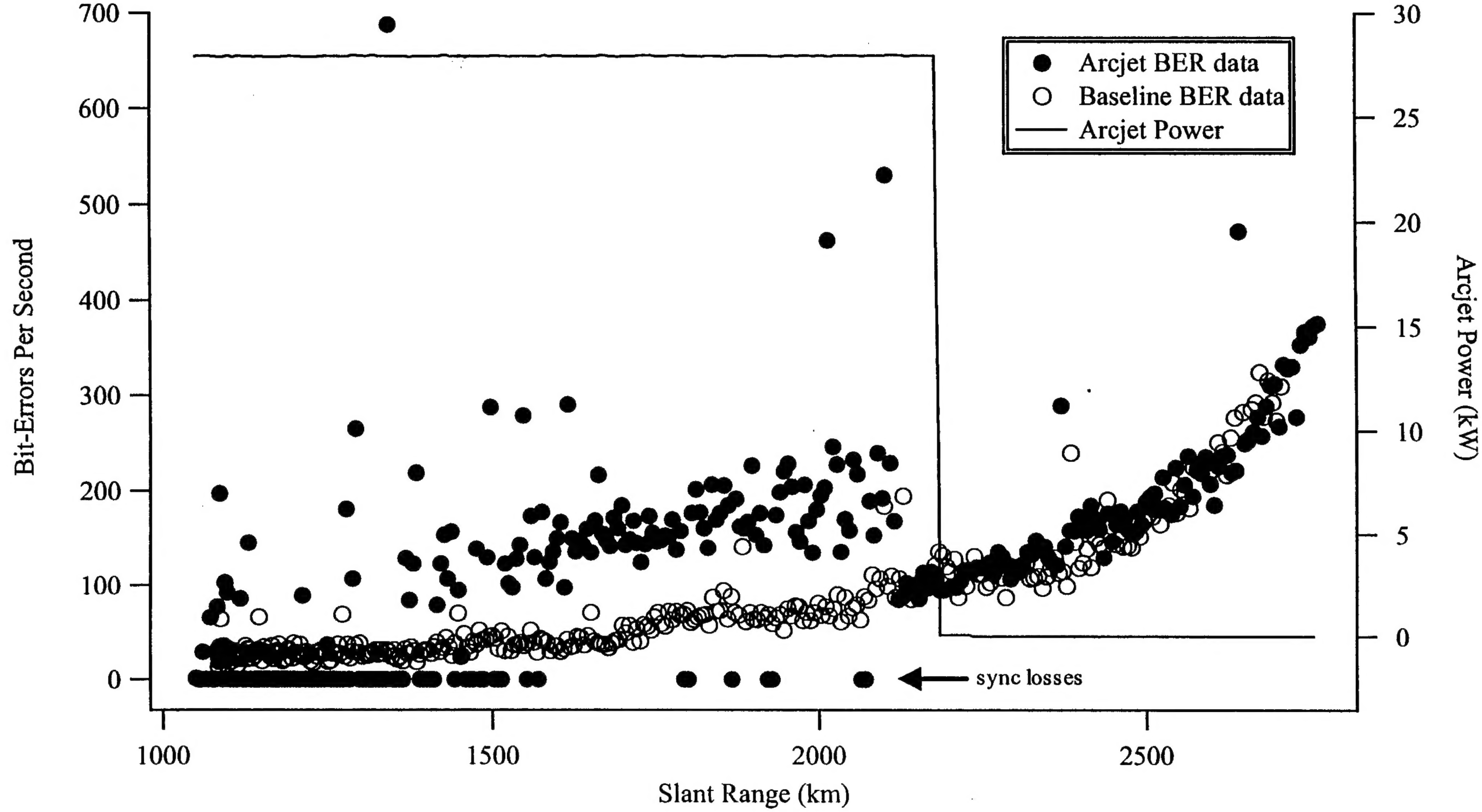


Figure 10 - Arcjet Firing # 4 BER Test

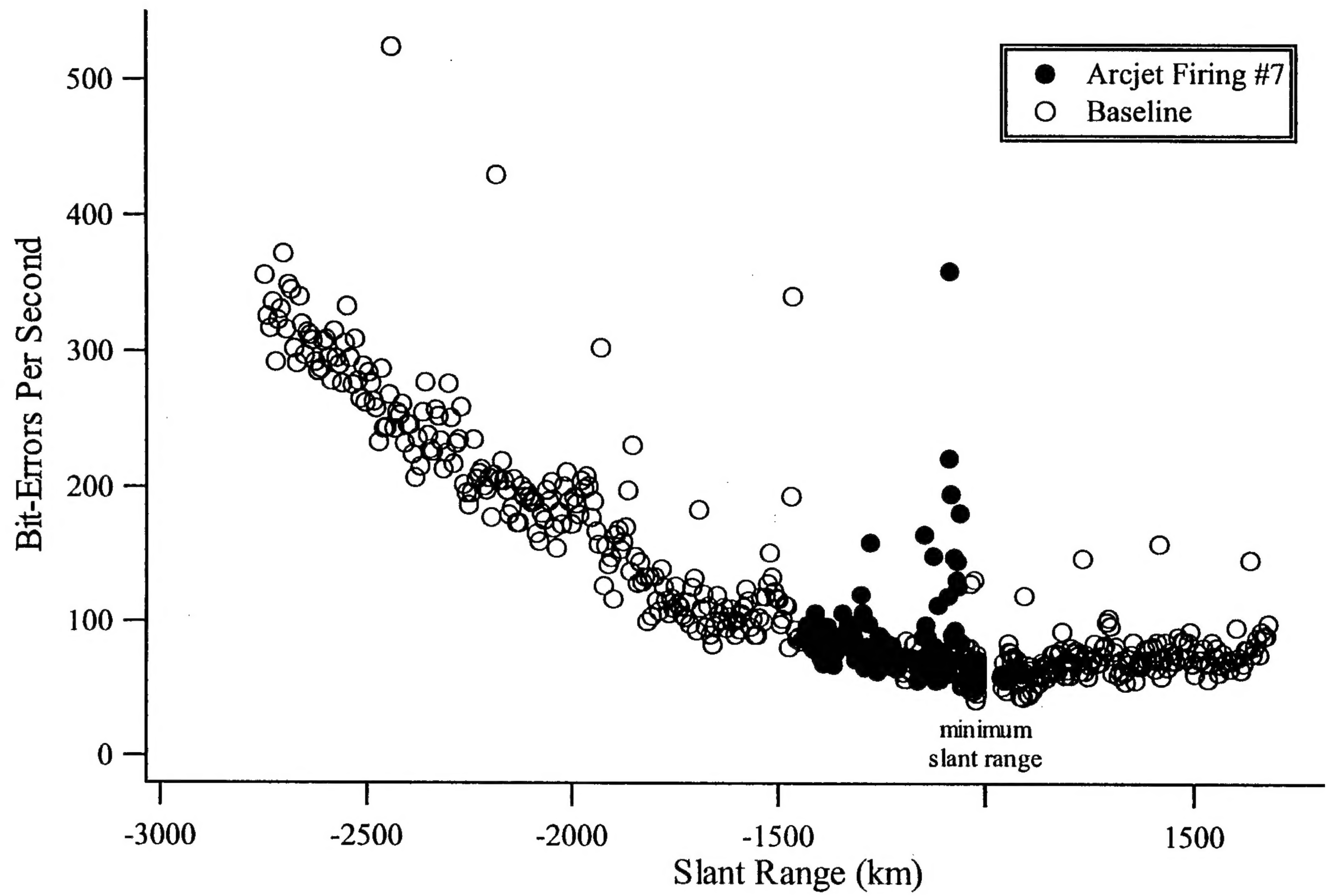


Figure 11 - Arcjet Firing # 7 BER Test

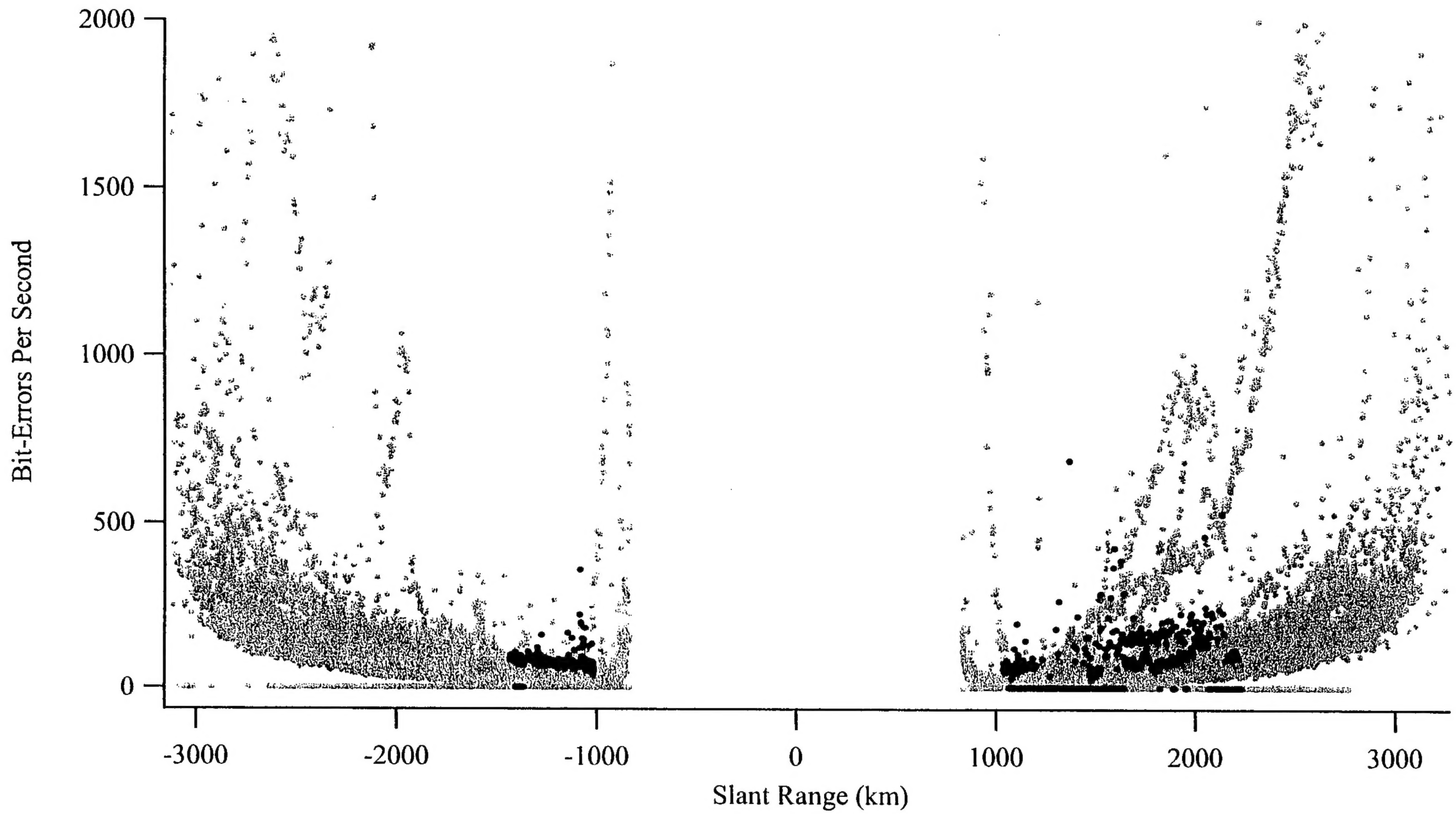


Figure 12 - Composite of 38 BER Test Results with Arcjet Firings # 2, # 4, and # 7 shown with black dots